VOLUME 76 SEPARATE No. 23

PROCEEDINGS

AMERICAN SOCIETY OF CIVIL ENGINEERS

JUNE, 1950

INFLUENCE OF HEAVY LOADS ON PAVEMENT DESIGN TRENDS

By K. B. Woods, M. ASCE

HIGHWAY DIVISION

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

PRICE $0.50 PER COPY

Published at Prince and Lemon Streets, Lancaster, Pa., by the American Society of Civil Engineers. Editorial and General Offices at 33 West Thirty-ninth Street, New York 18, N. Y. Reprints from this publication may be made on condition that the full title of paper, name of author, page reference, and date of publication by the Society are given.

AMERICAN SOCIETY OF CIVIL ENGINEERS
Founded November 5, 1852
PAPERS

INFLUENCE OF HEAVY LOADS ON PAVEMENT DESIGN TRENDS

By K. B. Woods,[1] M. ASCE

Synopsis

Highway pavement designs have been developed through extensive use of test roads, the use of theoretical or rational procedures—many of which have been checked by field tests and observations—and by the combined experiences of many highway engineers over a considerable period of time. These pavements, in general, proved to be adequate structurally for most sections of the United States for the period from 1920 to 1940.

Although information on the number and magnitude of loads which the highway systems carried through this period of time is somewhat meager, the available data, combined with general observations and experiences, point to the fact that the repetition of exceptionally heavy loads and the number of axle loads above 18,000 lb were relatively small in most places. In contrast, rigid pavements have failed and flexible pavements have become rutted on a considerable mileage of the primary systems of many states since about 1940—particularly in highly industrial regions or in other areas where high concentrations of heavy loads occur. The occurrence of this widespread distress and the violation of existing truck weight laws (although apparently limited to a small percentage of total trucks) show that the failure can be attributed almost entirely to overloads, or in some instances, to exceptionally high concentrations of loads at or near the maximum legal axle-load limit.

The following primary conclusions have been drawn: (*a*) Strict enforcement of weight laws must be pursued; (*b*) the prevailing legal axle-load limits must not be increased lest the existing highway systems be destroyed by loads in excess of those for which the pavements were designed and constructed; and (*c*) large-scale research on a national basis must be initiated immediately to determine the most economical design of both truck and pavement.

Note.—Written comments are invited for publication; the last discussion should be submitted by **December 1, 1950.**

[1] Associate Director, Joint Highway Research Project, and Prof. of Highway Eng., Purdue Univ., West Lafayette, Ind.

In connection with pavement design, available data indicate the need for better methods of compaction of base course materials for flexible and rigid pavements. Additional experimental work is needed to determine the economics and performance characteristics of rigid pavements constructed as thick slabs with heavy reinforcement or with various types and thicknesses of base courses.

Introduction

Early designs of flexible and rigid surfaces for the primary road systems within the United States have been developed by the use of test roads and other research procedures, by the accumulative experiences of design engineers and construction engineers, and by theoretical and rational analyses. The theoretical work and the data obtained from test roads established sound procedures for the design of rigid pavements in the early 1920's.

These designs, with some modifications throughout the years, proved to be reasonably adequate for primary roads throughout most sections of the United States. Because structural failures were not widespread, it is indicated that the designs were adequate for poor subgrade conditions and that these pavements were overdesigned for conditions of good subgrades. However, in the case of exceptionally heavy loads which occurred in fairly large concentrations in some sections of the East, these designs were not adequate and the use of base courses, thicker pavements, and modifications in joint design and reinforcing steel were required, notably in New Jersey.

During this same period of time (from 1920 through 1940) experiences were gradually accumulating for the design of flexible pavements. However, this situation is strikingly different from that of rigid pavements. Flexible pavements were developed during this period as a stage construction expedient rather than as a complete subgrade-pavement structure. As a result, data are somewhat meager in regard to the performance and thickness requirements of various types of bases and bituminous surfaces for the primary highway systems. This is particularly true in Indiana.

Two important conditions have altered the highway pavement design situation since 1940—namely, performance data accumulated in large-scale tests on runway pavements constructed to accommodate loads beyond those anticipated in highway use, and the destruction of rigid and flexible pavements on the primary highway systems of the United States which has been caused almost entirely by overloaded vehicles and extremely high concentrations of near-maximum legal loads. This destruction is evidenced in the pumping of rigid pavements and the rutting of flexible pavements.

Development of Designs for Rigid and Flexible Pavements

One of the earliest Portland cement concrete pavements built in the United States was constructed in 1891 in Bellefontaine, Ohio, and is still giving satisfactory service (1).[2] An extensive mileage of concrete was built in Wayne

[2] Numerals in parentheses, thus: (1), refer to corresponding items in the Bibliography (see Appendix).

County, Michigan, in the early 1900's. In about 1920, Portland cement concrete pavements began to be used on an increasingly greater scale for heavily traveled roads in New York, California, Ohio, Indiana, Illinois, and Iowa. Some of the early slabs were of 4-in. and 5-in. uniform thicknesses (2); but, after 1920, most slabs were 6 in. thick or more. Some of the early slabs contained a thickened middle; but, after about 1920, the thickened edge became important as a design feature (3). As a result of the data collected from the Bates test road (4)(5)(6) and the Pittsburgh, Calif., and Arlington, Va., test roads (7)(8), the thickened edge design became common practice, although 7-in. and 8-in. uniform thicknesses continued to be used in many sections of the United States. Until about 1940, reinforcement was confined largely to the use of marginal bars and to wire mesh (9)(10). The use of a center-line joint became accepted practice after about 1926; however, contraction joints and particularly expansion joints did not become standard practice for primary roads until about 1935 (11)(12).

The United States Public Roads Administration (PRA) has reported (8) (8*a*)(8*b*)(8*c*) some important data relative to the Arlington tests. Data on warping, load transfer at joints, and many other details are included in these reports. At a later time, E. F. Kelley (13)(13*a*) summarized the status of the design of Portland cement concrete pavements for highways. Theoretical aspects of pavement design have been given consideration for many years by H. M. Westergaard, M. ASCE (14).

The evolution of rigid pavement design in Indiana follows rather closely that used in many other states. M. R. Keefe (7) summarized the Indiana background data in 1940. The early design, 1919–1921, was a 6–8–6-in. plain plain concrete section; in 1922, a 7–8–7-in. slab replaced the early type. An 8-in. uniform slab was adopted in 1923, and in 1926 the state adopted the 9–7–9-in. cross section, with a $\frac{3}{4}$-in. marginal bar along each edge; and longitudinal joints were installed for the first time. Expansion joints were adopted as standard practice in 1934 and these devices were used until about 1944. At present (1950) Indiana does not use expansion joints, but contraction joints are employed. The thickness of the slab remains at 9–7–9 in.

F. H. Eno (15), the PRA, the State of Michigan, and others initiated early studies on subgrades, but the wide-scale use of base courses under rigid pavements in areas of plastic soils did not occur until 1935. In 1934 H. F. Janda (16) showed that there existed good correlation between certain types of concrete cracking and the type of subgrade soil. C. A. Hogentogler (17) made a statistical analysis of the performance of pavements in 1928 and showed a definite relationship between performance and soil textures.

Since the early 1930's much attention has been devoted to a study of the structural characteristics of subgrade soils—as these characteristics influence the design of rigid and flexible pavements. Plate loading tests have been used for evaluating subgrade soils for both types of pavements by W. S. Housel, M. ASCE (18), the United States Navy (19)(20), and the Asphalt Institute (21). A symposium on methods of conducting load bearing tests was published by the American Society for Testing Materials (ASTM) (22) in 1947. The California bearing ratio (CBR) test has been used extensively by California in the

design of flexible pavements for highways (23), the method being revised during World War II as a procedure for evaluating flexible pavements for military airfields (24)(25)(26). The triaxial compression test has been much used by many laboratories and an effort has been made to relate the structural characteristics of subgrade materials as indicated by this test, to pavement design requirements. The PRA has been active in this field (27), and the states of Kansas (28)(29) and Texas (30) have used this testing procedure extensively. W. Keith Boyd, M. ASCE (31), developed a cone test for evaluating subgrades and Fred Burggraf (32) developed a field-shear device. The California Department of Highways and other organizations (33) have conducted extensive experiments in the use of the Hveem stabilometer.

Macadam has been used for more than 150 years as a primary type of paving. The use of waterbound macadam and penetration macadam, with various types of bituminous-aggregate mixtures constructed as wearing courses, has prevailed in the United States for perhaps 75 years. However, flexible pavements have been employed primarily as resurfacing courses, and it has been only in recent years that any great amount of attention has been given to thickness design as it pertains to the subgrade-base-wearing-course combination. Sheet-asphalt and bituminous-concrete surfaces have been employed extensively, particularly in cities, but these types were often constructed over rigid bases or over some type of graded-aggregate mixture which had been under traffic for varying periods of time.

Just preceding and during World War II, many investigators were engaged in developing information on the design of flexible pavements. Prominent reports included those by A. C. Benkelman (34); W. H. Campen, M. ASCE, and J. R. Smith (35); A. T. Goldbeck, M. ASCE (36); Prevost Hubbard, Affiliate, ASCE, and F. C. Field (37); M. G. Spangler, M. ASCE (38); Roland Vokac (39); the committees of the Highway Research Board (HRB), National Research Council (40)(41)(42); A. T. Britton (43); F. N. Hveem, Assoc. M. ASCE (44); and G. E. Hawthorn (45). In addition, widespread interest has been shown in certain sections of the Great Plains, the West, and in the Middle West in the design of flexible pavements for use in secondary and even primary pavements. In addition to the reports from Texas and Kansas, mentioned previously, reports from New Mexico (46), Wyoming (47), Michigan (48), Minnesota (49), the western states (50), Missouri, and Kentucky, merit special mention. The reports on Missouri and Kentucky were received in letters from F. V. Reagel (February 21, 1949) and L. E. Gregg, Assoc. M. ASCE (March 9, 1949), respectively.

As a result of large-scale construction of civilian and military airports since about 1940, added emphasis has been given to the problem of pavement design—both flexible and rigid. Mr. Westergaard (51)(52) has extended his theoretical analysis of rigid pavement design to include loadings far beyond those which could reasonably be anticipated on highways. Robert R. Philippe, Assoc. M. ASCE (53)(54), has reported the results of extensive outdoor experiments with various types of rigid pavement slabs which were tested to failure. Both the United States Engineer Department (55)(56)(57)(58)(59)(60) and the United States Navy (61)(62) have released extensive reports covering the test-

ing to failure of sections of airport runways at a variety of locations and situated on a large range of soil types. As a result of large-scale performance surveys of highways (63)(64) and of airports, there can be little doubt that the soil variable is a very important one and will become increasingly more important as conditions of loading become more severe.

Trend in Traffic Loads

Limited data are available in regard to the number and magnitude of wheel and axle loads previous to 1935. At that time, PRA, in cooperation with most state highway departments, initiated programs of traffic counts and weight studies, and the collection of other types of factual data through the facilities of planning surveys. Robley Winfrey, M. ASCE (65), in 1935 reported data on actual service lives of pavements, but these data were not tied in with the most important condition of service—that is, loads. Rex M. Whitton (66) emphasizes the axle-load factor, stating (66*a*) that: "Most engineers agree that damage to road surfaces caused by overloading is due to wheel or axle loading and not to gross loading."

It is apparent that in the 1920's and 1930's primary highway systems carried but very few axle loads in excess of 18,000 lb. Furthermore, the number of repetitions of the 16,000-lb axle loads to the 18,000-lb axle loads was much smaller in this period than was true in the years following 1940.

Some of the truck-weight information collected by the PRA and many of the state highway departments was summarized by John T. Lynch, Assoc. M. ASCE (67), in 1942. He concluded in part that, since the original loadometer operations in the period from 1936 to 1940, the frequency of heavy axle loads had increased materially in all regions of the United States. In this same paper, Mr. Lynch reported a large number of axle loads in the 20,000-lb to 22,000-lb range and a surprisingly great number more than 22,000 lb. The next year, Mr. Lynch (68) wrote (68*a*):

> "The average number of heavy axle loads passing each survey station in the 8 hours of operation was much greater in 1942 than in the 1936–1940 period, but was only slightly greater in 1943 than in 1942."

Thomas B. Dimmick in 1946 (69) supplied information on heavy axle-load frequency from data obtained in 1943 and 1944. This report grouped the data into frequency of axle loads between 14,000 lb and 16,000 lb, between 16,000 lb and 18,000 lb, and 18,000 lb and more. A large number of axle loads was reported in the 18,000-lb, and more, class (for the three eastern census regions, about 150 axles per 1,000 commercial vehicles daily being in the 18,000-lb, and more, class); unfortunately, information on the weight of the heaviest axle loads was not included.

In 1947, the writer, with F. H. Green, M. ASCE, and Harold S. Sweet, Jun. ASCE (70), made an analysis of the planning survey truck-weight data for Indiana, establishing a correlation between overloads and pavement destruction. Truck-weight data were available from twenty weighing stations for the years, 1936, 1942, 1943, 1944, and 1946. Survey procedure consisted of counting all vehicles and weighing trucks at each station for 8 hours, once each year.

The report showed a general relative decrease in the number of 10,000-lb loads and 14,000-lb loads since about 1943. In contrast, the number of axle loads of 18,000 lb, and more, showed a steady increase from 1936 with a material rise in 1946. Likewise, the number of axle loads greater than 20,000 lb increased significantly about 1944.

The maximum legal axle load in Indiana is 18,000 lb. A summary of the number of axles and the corresponding loads in excess of 18,000 lb, of one 8-hr period per station per year for all twenty Indiana stations in 1948 is shown in Table 1. It is to be noted that a few axle loads are in excess of 32,000 lb. The summary of the number of axle loads greater than 18,000 lb for the 8-hr survey at all twenty stations, in Table 2 shows a large increase in the number of violations in comparing 1946 and 1947 with 1942, 1943, and 1944.

TABLE 1.—AXLE WEIGHTS IN EXCESS OF LEGAL LIMIT OF 18,000 LB IN 1948 SURVEY (TOTAL OF 369 AXLES ON 289 TRUNKS AND COMBINATIONS

Axle weight (lb) (1)	No. of axles (2)	Axle weight (lb) (1)	No. of axles (2)	Axle weight (lb) (1)	No. of axles (2)	Axle weight (lb) (1)	No. of axles (2)	Axle weight (lb) (1)	No. of axles (2)
18,200	34	20,000	17	21,800	5	23,800	1	26,400	1
18,400	33	20,200	8	22,000	12	24,000	3	26,600	1
18,600	30	20,400	10	22,200	2	24,200	2	26,800	1
18,800	28	20,600	9	22,400	4	24,400	2	27,400	1
19,000	27	20,800	11	22,600	5	24,600	1	27,800	1
19,200	22	21,000	11	22,800	2	25,000	1	28,400	1
19,400	23	21,200	7	23,000	2	25,200	1	28,800	1
19,600	21	21,400	4	23,200	1	25,400	1	30,000	1
19,800	13	21,600	4	23,600	2	26,000	1	32,000	1

TABLE 2.—SUMMARY OF LOADS GREATER THAN 18,000 LB

Description	No. of Trucks and Combinations				
	95	98	71	230	217
Number of axles loaded more than 18,000 lb	116	118	75	289	274
Year recorded	1942	1943	1944	1946	1947

In testing airport runways, wheel loads of from 20,000 lb to 35,000 lb are common (55)(61), with extreme loads as high as 150,000 lb or more (53). These are much higher than most highway loads, although this variation may not be as great as indicated at first inspection, when consideration is given to some of the exceptionally high illegal highway loads as well as to the repetition-of-load factor.

STRUCTURAL FAILURES OF PAVEMENTS

Failures of primary pavements because of structural deficiencies were not widespread previous to about 1940. Failures were observed in some instances where pavements were too thin or in locations of frost heave, peat bog subsidences, or embankment settlement (particularly at culverts and bridge approaches), and in certain specific areas of high concentrations of heavy loads.

During certain seasons, adverse climatic influences contributed to the deterioration. These rather occasional failures probably had considerable influence in the development of better procedures for subgrade and embankment compaction, methods for handling peat bogs, subgrade treatments to control frost heave, and for posting roads during the spring breakup period (71).

In the years just preceding World War II, this condition changed significantly and structural failures became common on the primary system throughout many sections of the United States. These failures invariably occurred on roads that carried a heavy volume of truck traffic, covering areas where the subgrade materials were predominantly claylike or plastic in character (Fig. 1). Many rigid pavements were destroyed by pumping (72), and many flexible pavements showed a marked tendency toward rutting in the wheel tracks (Fig. 2).

Pumping, as a primary problem in Indiana, was first noted in 1940 (72). Short sections of several primary roads in the northwest corner of the state and in some sections near Fort Wayne were the first to be in distress. Extensive performance surveys in 1940–1941 failed to show structural failures to any great extent, as stated in unpublished reports of the Joint Highway Research Project at Purdue University in West Lafayette, Ind., in 1940 and 1941. However,

FIG. 1.—NEAR FAILURE ON OUTSIDE LANE OF DUAL LANE PAVEMENT CAUSED BY PUMPING

this problem became severe during World War II, and in 1943 most of the rigid pavements in the state were surveyed to determine the extent and magnitude of the failures. Primary attention was given also to the spring breakup of flexible pavements. These data were reported at the 1943 meeting of the

HRB (72). It is pertinent to note that 245.4 miles of pumping pavements was reported in the entire state. At that time, it was apparent that the soil variable was an important one because pumping was limited to sections of primary

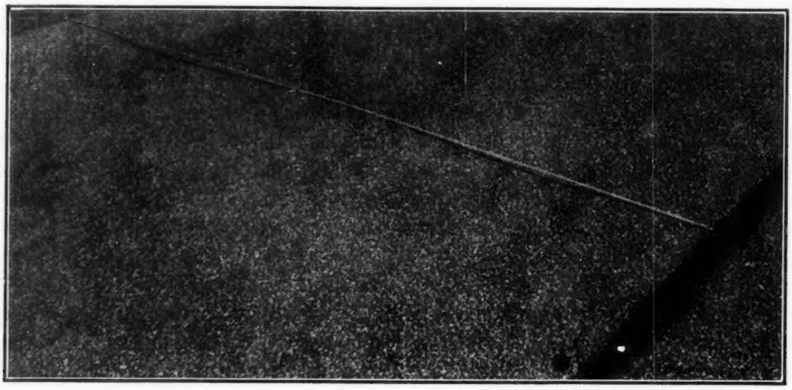

FIG. 2.—RUTTING OF A BITUMINOUS CONCRETE PAVEMENT

roads located in plastic soil areas. It was also obvious that the number and the magnitude of truck loads were important variables since pavement pumping was confined to the primary truck routes. Pavements on secondary roads with comparable designs, ages, and subgrade soils did not pump.

By 1947, the problem of pumping was widespread in the State of Indiana, and this fact led to a resurvey of the primary highway system, which showed (70) that the mileage of pavement pumping had almost doubled between 1943 and 1947. When the performance-survey data were correlated with the truck-weight data, it was indicated that the pumping in Indiana was directly related to the number and magnitude of overloads. The second report confirmed the data reported in 1943, pumping being confined to the heavily traveled truck routes located on plastic soils. However, it was noted that the problem had spread into areas of soils of lower plasticity than was true at the time of the 1943 survey. Furthermore, 47.8 miles of pavements constructed on deep sand subgrades were faulted, although they were not pumping. This circumstance was important in considering the use of these same materials as granular bases to eliminate pavement pumping in plastic soil areas.

Early mention of pavement pumping was made by J. W. Poulter (73) in connection with the use of mudjack materials to correct pumping pavements and faulted joints. The Illinois Division of Highways reported difficulty with pumping in 1939 (74), and the HRB appointed a committee to study the problem in 1942 (75). Detailed surveys have been made by various state highway departments in cooperation with the Portland Cement Association (76) (77). Field studies have been made in regard to the effect of the various design features including the thickened edge, expansion and contraction joints, the type of subgrade soil, and the use of various types and gradations of base courses. The work of the HRB committee confirms that pavement pumping is on the increase, that it occurs in areas of claylike materials, and that it is limited to roads which are subjected to a large number of heavy loads (78).

Information on the failures of flexible pavements as related to loads is meager. As mentioned previously, the use of flexible pavements has been widespread for secondary roads and as resurface materials for primary roads, at least in the Middle West—particularly in Indiana. As a result, the field-performance data on thickness requirements for the base-pavement combination are adequate for drawing only tentative conclusions. In two or three instances in Indiana, waterbound macadam bases with bituminous concrete surfaces have been constructed adjacent to Portland cement concrete pavements, which have been in distress from pavement pumping. In two instances, the bituminous surfaces have shown definite signs of rutting, thus indicating that the overload problem is of some consequence to this type of pavement also. In accelerated traffic tests on flexible airfield pavements Mr. Boyd (60) shows extensive rutting on pavements tested to failure. A similar type of failure is shown by F. A. Robeson (56).

Design Features Related to Structural Behavior

In considering the problem of pavement pumping as related to the design features of rigid pavements, it is significant that the problem has occurred on pavements with a wide range in design features and a wide range of pavement ages. In Indiana, pumping has occurred on 25-yr-old pavements with a thickened middle; it has been evident on pavements of uniform thicknesses ranging from 6 in. to 8 in.; and pumping has prevailed on the old Bates type of design, such as a 9–7–9-in. cross section with longitudinal bar or wire mesh reinforcement and without expansion or contraction joints. Some modern pavements with contraction and expansion joints, or with expansion joints alone, have pumped within 2 years or 3 years after construction. Many of these same roads, or roads of similar designs, carried highway traffic for years without encountering widespread structural failures preceding 1940. It must be concluded, therefore, that the entire range of designs was inadequate to carry the overloads to which they were abruptly subjected, and that minor variations in design had little to do with the problem of pumping. Certain features of design, however, are prominent and should be emphasized.

In regard to thickness of rigid pavements, available information indicates that pavement pumping is not eliminated on claylike subgrades by lightly reinforced slabs up to 10 in. thick. Pavements of thicknesses less than 10 in. have been giving good service for many years on primary roads in Indiana when subgrades are predominantly granular.

In analyzing the large amount of field information available on pumping, it is apparent that joints, particularly poorly maintained expansion joints, contribute appreciably to the problem. Since considerable data already indicate that expansion joints are not generally required on highway pavements (79)(80)(80*a*), it appears that the elimination of this design feature will greatly improve structural efficiency. Mr. Kelley (81) recognized this possibility in 1940 when he stated (81*a*) that some engineers conclude:

> "* * * when expansion joints are used it is not necessary to provide enough expansion space to effect complete relief of restraint but on the contrary, it is desirable from a structural standpoint to provide only enough space to keep compressive stresses within safe limits."

The State of New Jersey (82) requires the use of expansion joints, but an endeavor is made to keep the pavement in compression and to provide adequate load transfer between slabs at joints.

Contraction joints, as well as longitudinal joints, cause some difficulty from the standpoint of pumping, but their use can scarcely be considered a primary cause. There can be little argument in regard to the need for the longitudinal joint; and, since most design engineers feel the need for contraction joints as a method of controlling cracking, it is likely that these design features will be continued. More emphasis will be given to methods of maintaining joints.

Increased attention will doubtless be paid subgrade soil and design will include the factor of subgrade soil type as an integral part of the subgrade-base-pavement combination. With pumping being almost entirely confined to plastic soils, and with the available evidence pointing to the potential severity of rutting of bituminous pavements on these same soils, the soil variable indeed appears to be the most important of all design factors.

Drainage and associated maintenance must continue to be considered important. Since water is one of the most important factors involved in the problem of pumping, extra precautions should be taken in the original design to keep the pavement and subgrade as dry as possible. Coupled with drainage should be maintenance policies that require a periodic sealing of all cracks and joints to minimize the seepage of surface water into the subgrade.

Design Trends

If a design procedure must be established to construct pavements that will perform reasonably well for high concentrations of legal loads as well as for illegal loads, it is appropriate to consider design trends. As far as rigid pavements are concerned, much study is being given to the use of heavily reinforced slabs as contrasted to the improvement of poor subgrades and the use of base courses. As to bituminous pavements, there is a trend toward the use of macadam bases, and much thought is being given to methods of compacting granular materials in base courses. The compaction of granular base courses for rigid pavements is equally important.

The PRA, in cooperation with the State Highway Commission of Indiana, constructed several miles in test sections of continuously reinforced concrete pavements in 1938. Reports of the performance of these sections have been made available at periodic intervals (83)(84)(85). As pavement pumping has increased through the past several years, more and more attention has been given to these experimental sections. Since about 1946, several additional experimental test sections have been constructed in other states. In 1947, H. W. Russell and J. D. Lindsay (86) reported on such a pavement constructed in Illinois, and in the same year William Van Breemen (87) made a similar report on a project in New Jersey. W. R. Woolley (88) has been interested in the use of this type of pavement design, particularly from the standpoint of the elimination of expansion joints and susceptibility to pumping. Additional data will be required and perhaps several years of service testing will be needed before this type of design can be evaluated fully. However, continuous reinforced concrete design remains as one of the outstanding potential solutions to the destructive forces of a large number of excessively heavy axle loads.

Experiments with base courses have been conducted for many years, particularly in connection with subgrade treatment to prevent frost heave, to improve drainage, and, more recently, to eliminate pavement pumping. From the standpoint of pumping, it appears that the base course serves most effectively as an insulation between pavement and subgrade rather than as an addition to improve the structural capacity.

E. A. Henderson and W. T. Spencer (89) reported important data in regard to 10-yr-old experimental base course sections on U. S. Highway No. 30 in Indiana. The treatments included eight different base courses, varying in type from bituminous soil mixtures to limestone screenings and dune sands. Thicknesses of treatment ranged from 3 in. to 6 in. Small amounts of bituminous materials mixed with plastic subgrade soils reduced pavement pumping markedly. The dune sand was particularly effective in eliminating pumping, but the faulting at joints was of measurable and noticeable amounts. This observation, coupled with other performance-survey data showing considerable amounts of faulting on heavily traveled pavements constructed on deep sand-soils, indicates that the sand is being further compacted under the pavement slab by the vibration resulting from repetitions of heavy loads. This being true, precautions need be taken against the use of a deep layer of poorly graded, granular base courses and, in addition, special emphasis must be given to compaction during construction (90).

As far as rigid pavements are concerned, it appears that heavy duty pavements for truck routes will require either 8-in. to 10-in. slabs with heavy reinforcement, or thinner slabs with less reinforcement, underlain by well compacted base courses. As an economical expedient in some areas well graded granular materials (91)(92) and treated bases (93)(94) should be used. The selection of bituminous and concrete overlays to strengthen pavements which are structurally inadequate will probably continue as good design practice (95)(96); however, experience indicates that moving slabs must be stabilized before overlays can be used satisfactorily.

In regard to flexible pavements, the trend appears to be toward the use of waterbound macadam bases of considerable thickness, or selected granular materials with base and surface courses constructed of bituminous concrete (95). With the tendency toward rutting, it appears that additional emphasis must be placed on methods and procedures that can be employed during construction to obtain greater compaction of the granular materials. The use of small amounts of liquid bituminous material or cement as binder may partly solve the problem; the development of some method of hardening a claylike soil may be a partial answer to obtaining higher densities in the compaction of base course materials on claylike subgrades.

It appears at the present time that the large amount of data collected on the design of thick rigid and flexible surfaces for exceptionally heavy airplane loads cannot be applied directly to the design of highway pavements because of two factors: (*a*) The repetition of load on a highway pavement is considerably greater than that which can be expected on a normal airport runway or taxiway, and (*b*) the wheel loads and impact factors for trucks and other heavy vehicles using the highway are entirely different from those of the airplane.

Summary

On the basis of published information, field test sections, and performance records of pavements in Indiana and many additional states, data available on the effect of heavy loads on pavement design may be summarized as follows:

1. The subgrade soil is the most important variable and the one which has received insufficient attention in the design of rigid and flexible pavements for roads carrying heavy industrial traffic. The performance information available shows a correlation between performance and soil texture—with drainage properties and position of the road surface in respect to the surrounding terrain being only slightly less important.

2. The most perplexing unknowns in connection with the design of rigid and flexible pavements for roads carrying heavy truck traffic are those of the ultimate number and magnitude of the loads themselves. Designs for rigid pavements developed on the basis of theoretical analysis, test roads, and field experiences have proved to be reasonably adequate for the period from 1920 to 1940 in most sections of the United States when loads were rarely in excess of the legal limit. In contrast, widespread structural failures have occurred and are continuing to occur on the roads of the primary systems of several states, including Indiana, in which illegal loads of considerable magnitude have become frequent in occurrence. Available truck-weight data show that the frequency of illegal loads has increased steadily since about 1940, and that the magnitude of these loads, particularly axle loads, is still increasing.

3. Corrective procedures to meet the present emergency should include: (*a*) Strict enforcement of existing weight laws, particularly axle loads; (*b*) the adoption of a policy by the state highway departments whereby salvage operations—including the stabilization of pumping slabs and the use of overlays—will be attempted in the early stages of pumping; and (*c*) the posting of roads and the establishment of load limits during the spring breakup period in an endeavor to protect existing pavements which are structurally inadequate.

4. In considering the generally established design procedures for rigid pavement available data indicate that these are inadequate—particularly from the standpoint of subgrade soil evaluation. Furthermore, it is indicated that the thickened edge, thickened middle, and other minor variations are relatively unimportant from the standpoint of pavement pumping; however, the elimination of expansion joints should improve the structural efficiency of rigid pavements, although this change alone will not necessarily eliminate the difficulty. It has not been proved thus far that pavement pumping can be eliminated by thick pavements, up to 10 in. In Indiana there are many hundreds of miles of pavements constructed with an old Bates type of design (9–7–9-in. cross section with longitudinal bars or wire mesh reinforcement) giving excellent performance after 20 years or more of life. These roads are located on "nontruck" routes and have been placed on a wide variety of soils with claylike materials predominating. In contrast, most of the pavements of this type of design, located on primary routes have been resurfaced or destroyed. These data indicate that this type of design is adequate for carrying only a small number of trucks, but that it is inadequate for primary roads under present loadings. In regard to flexible pavements, there is evidence that rutting of the surface occurs on

pavements carrying heavy truck loads and constructed on plastic soils. This research should be directed toward compaction requirements for the subgrade and base. Also, research is needed to establish thickness requirements of the base-pavement combination for prevailing conditions of loading. The use of nonplastic bases or bases with low plasticity indexes, as well as cement—or bituminous-treated granular bases—is indicated for both secondary and primary roads particularly in the midwestern and western states.

5. In regard to design trends, from currently available information, it appears that rigid pavements will be designed by one of two procedures: (*a*) The use of soil treatments to correct inferior subgrades, the additional use of base course, and the employment of slabs of medium thickness and reinforcement of some standard type of design of the slab; and (*b*) the use of thicker slabs with continuous reinforcement and the elimination of all the transverse joints. In general, longitudinal joints and contraction joints are likely to continue in standard practice, but the trend is definitely away from expansion joints. In connection with flexible pavements, the available data show that new methods and procedures for compacting subgrades and bases to obtain a maximum of strength from the pavement-base-subgrade combination are needed, and research on base course materials and admixtures should be continued. As to soils, there is a basic need to evaluate soils and constructional materials on a regional basis and thus to standardize design by soil regions rather than by political boundaries.

6. The establishment of large-scale research programs is required, preferably on a national basis, to determine the most economical design of both the truck and the pavement. In this respect, the states can obtain excellent preliminary information by contracting for the construction of test sections. These sections should include various thicknesses of rigid and flexible pavements over various types and thicknesses of base courses on both the primary and secondary road systems.

Acknowledgment

This paper was developed from published information, research work conducted at Purdue University, and experiences thus gained in evaluating the variables of soils, climate, traffic, and materials as they relate to the performance of primary pavements.

APPENDIX. BIBLIOGRAPHY ON PAVEMENT DESIGN FOR HEAVY LOADS

---

(1) **"First Concrete Paving 50 Years Old,"** by Tracy Bartholomew, *Engineering News-Record*, August 28, 1941, p. 57.

(2) **"Thickness of Concrete Slabs,"** by A. T. Goldbeck, *Public Roads*, 1919, pp. 34–38.

(3) **"Stresses in Concrete Pavements Computed by Theoretical Analysis,"** by H. M. Westergaard, *ibid.*, April, 1926, p. 25.

(4) **"Highway Research in Illinois,"** by Clifford Older, *Transactions*, ASCE, Vol. LXXXVII, 1924, p. 1180.

(5) **"Bates Experimental Road,"** by Clifford Older, *Bulletin No. 18*, Illinois Dept. of Public Works and Buildings, Div. of Highways, Springfield, Ill., 1924.

(6) **"Study of the California Highway System,"** Div. of Highways, California Dept. of Public Works, Sacramento, Calif., 1920.

(7) **"Pavement Design,"** by M. R. Keefe, *Proceedings*, 26th Annual Road School, *Extension Series No. 47*, Purdue Univ., Lafayette, Ind., July, 1940, pp. 47–52.

(8) **"The Structural Design of Concrete Pavements,"** by L. W. Teller and Earl C. Sutherland, *Public Roads*, Vol. 16, 1935, Pt. 1, pp. 145–158. (*a*) Pt. 2, pp. 169–197. (*b*) Pt. 3, pp. 201–221. (*c*) Vol. 17, 1936, Pt. 4, pp. 143–171 and pp. 175–192.

(9) **"Functions of Steel Reinforcement in Concrete Pavements and Pavement Bases,"** by C. A. Hogentogler, E. A. Willis, and F. A. Robeson, *Proceedings*, Highway Research Board, National Research Council, Vol. 11, 1931, Pt. I, pp. 271–309.

(10) **"The Interrelation of Longitudinal Steel and Transverse Cracks in Concrete Roads,"** by A. T. Goldbeck, *Public Roads*, August, 1925, p. 117.

(11) **"Dowels and Joint Fillers in Concrete Paving,"** by R. E. Toms, *Engineering News-Record*, February 28, 1935, p. 318.

(12) **"Load Transfer at Transverse Joints an Economic Necessity,"** by Clifford Older, *ibid.*, May 23, 1935, p. 746.

(13) **"Application of the Results of Research to the Structural Design of Concrete Pavements,"** by E. F. Kelley, *Public Roads*, July, 1939, Pt. I, p. 83. (*a*) August, 1939, Pt. II, p. 107.

(14) **"Design of the Cross-Section,"** by H. M. Westergaard, *Proceedings*, Highway Research Board, National Research Council, Vol. 8, 1928, p. 159.

(15) **"Some Effects of Soil, Water, and Climate Upon the Construction, Life, and Maintenance of Highways,"** by F. H. Eno, *Bulletin No. 85*, Eng. Experiment Station, Ohio State Univ., Columbus, Ohio, November, 1934.

(16) **"Longitudinal Cracking of Concrete Pavements on State Highway 13 in Clark and Taylor Counties, Wisconsin,"** by H. F. Janda, *Proceedings*, Highway Research Board, National Research Council, Vol. 15, 1935, p. 157.

(17) **"Important Developments with Respect to Subgrade Investigations,"** by C. A. Hogentogler and Henry Aaron, *ibid.*, Vol. 9, 1929, pp. 249–275.

(18) **"Load Tests on Flexible Surfaces,"** by W. S. Housel, *ibid.*, Vol. 21, 1941, pp. 118–136.

(19) **"Procedure for Determination of Thickness of Flexible Type Pavements,"** *Manual No. 1*, Bureau of Yards and Docks, U. S. Navy Dept., Washington, D. C., March, 1943 (revised June, 1943).

(20) **"Procedure for Determination of Thickness of Rigid Type Pavements,"** *Manual No. 2*, Bureau of Yards and Docks, U. S. Navy Dept., Washington, D. C., June, 1943.

(21) **"Flexible Pavement Reaction Under Field Load Bearing Tests,"** by Prevost Hubbard, *Research Series No. 9*, Asphalt Inst., May 5, 1943.

(22) **"Symposium on Load Tests of Bearing Capacity of Soils,"** *Special Technical Publication No. 79*, A.S.T.M., Philadelphia, Pa., June, 1948.

(23) **"Foundations for Flexible Pavements,"** by O. J. Porter, *Proceedings*, Highway Research Board, National Research Council, Vol. 22, 1942, pp. 100–143.

(24) **"Soil Tests for Design of Runway Pavements,"** by T. A. Middlebrooks and G. E. Bertram, *ibid.*, pp. 144–173.

(25) **"The California Bearing Ratio Test As Applied to the Design of Flexible Pavements for Airports,"** *Technical Memorandum No. 213-1*, U. S. Waterways Experiment Station, Vicksburg, Miss., 1 July, 1945.

(26) **"Development of CBR Flexible Pavement Design Method for Airfields: A Symposium,"** *Proceedings*, ASCE, January, 1949, pp. 3–104.

(27) **"Application of Triaxial Compression Test Results to the Calculation of Flexible Pavement Thickness,"** by E. S. Barber, *Proceedings*, Highway Research Board, National Research Council, Vol. 26, 1946, pp. 26–39.

(28) **"Triaxial Testing Methods Usable in Flexible Pavement Design,"** by Herbert E. Worley, *ibid.*, Vol. 23, 1943, pp. 109–116.

(29) **"Design of Flexible Pavements Using the Triaxial Compression Test,"** *Bulletin No. 8*, Highway Research Board, National Research Council, September, 1947.

(30) **"Progress Report on Development and Use of Strength Tests for Subgrade Soils and Flexible Base Materials,"** by Chester McDowell, *Proceedings*, Highway Research Board, National Research Council, Vol. 26, 1946, pp. 484–511.

(31) **"An Analysis of Wheel Load Limits As Related to Design,"** by Keith Boyd, *ibid.*, Vol. 22, 1942, pp. 185–198.

(32) **"Field Tests on Shearing Resistance,"** by Fred Burggraf, *ibid.*, Vol. 19, 1939, pp. 484–490.

(33) **"Applications of the Mohr Circle and Stress Triangle Diagrams to Test Data Taken with the Hveem Stabilometer,"** by L. E. McCarty, *ibid.*, Vol. 26, 1946, pp. 100–123.

(34) **"What We Know About the Design of Pavements of the Flexible Type,"** by A. C. Benkelman, *ibid.*, Vol. 17, 1937, pp. 144–145.

(35) **"Measuring the Load Supporting Value of Flexible Pavements,"** by W. H. Campen and J. R. Smith, *ibid.*, Vol. 21, 1941, pp. 142–146.

(36) **"A Method of Design of Non-Rigid Pavements for Highways and Airport Runways,"** by A. T. Goldbeck, *ibid.*, Vol. 20, 1940, pp. 258–270.

(37) **"Required Thickness of Asphalt Pavement in Relation to Subgrade Support,"** by Prevost Hubbard and F. C. Field, *ibid.*, pp. 271–278.

(38) **"The Structural Design of Flexible Pavements,"** by M. G. Spangler, *ibid.*, Vol. 22, 1942, pp. 199–224.

(39) **"Thickness of Surface and Base Courses for Flexible Pavements,"** by Roland Vokac, *ibid.*, Vol. 23, 1943, pp. 155–165.

(40) **"Thickness of Flexible Pavements for Highway Loads,"** *Wartime Road Problem No. 8R*, Highway Research Board, National Research Council, November, 1949.

(41) **"Methods of Designing Thickness of Flight Strips and Airport Runways for Wheel Loads Exceeding 10,000 Lb.,"** *Proceedings,* Highway Research Board, National Research Council, Vol. 23, 1943, pp. 90–100.

(42) **"Progress Report of Subcommittee on Methods of Measuring Strength of Subgrade Soil—Review of Methods of Design of Flexible Pavements,"** *ibid.,* Vol. 25, 1945, pp. 8–18.

(43) **"Flexible Pavements—Design and Selection of Materials,"** by A. T. Britton, *ibid.,* Vol. 27, 1947, pp. 104–125.

(44) **"A New Approach for Pavement Design,"** by F. N. Hveem, *Engineering News-Record,* July 8, 1948, p. 134.

(45) **"The Design and Construction of Nonrigid Pavements,"** by G. E. Hawthorn, *Proceedings,* Am. Road Builders' Assn., 1939, p. 161.

(46) **"A Method for Estimating Required Thicknesses of Flexible Base,"** by E. B. Bail, *Proceedings,* Highway Research Board, National Research Council, Vol. 27, 1947, pp. 98–104.

(47) **"Wyoming Method of Flexible Pavement Design,"** by I. E. Russell and D. J. Olinger, *ibid.,* pp. 84–91.

(48) **"Design of Flexible Surfaces in Michigan,"** by W. W. McLaughlin and O. L. Stokstad, *ibid.,* Vol. 26, 1946, pp. 39–44.

(49) **"Development of a Procedure for the Design of Flexible Bases,"** by J. H. Swanberg and C. C. Hansen, *ibid.,* pp. 44–57.

(50) **"Highway Design Trends in the Western States,"** by C. D. Vail, *Civil Engineering,* September, 1940, pp. 567–570.

(51) **"Stresses in Concrete Runways of Airports,"** by H. M. Westergaard, *Proceedings,* Highway Research Board, National Research Council, Vol. 19, 1939, pp. 197–202.

(52) **"New Formulas for Stresses in Concrete Pavements of Airfields,"** by H. M. Westergaard, *Transactions,* ASCE, Vol. 113, 1948, pp. 425–444.

(53) **"Runways for Seventy-Five-Ton Wheel Loads,"** *Engineering News-Record,* March 4, 1948, pp. 82–87.

(54) **"Full-Scale Research Advances Design of Rigid Pavements for Heavy Wheel Loads,"** by Robert R. Philippe, *Civil Engineering,* February, 1948, pp. 32–36.

(55) **"Results of Accelerated Traffic Tests of Runway Pavements,"** by T. A. Middlebrooks and R. M. Haines, *Proceedings,* Highway Research Board, National Research Council, Vol. 23, 1943, pp. 101–108.

(56) **"Accelerated Traffic Tests at Eglin Field, Florida,"** by F. A. Robeson, *ibid.,* Vol. 24, 1944, pp. 55–70.

(57) **"Accelerated Traffic Test at Langley Field, Virginia,"** by D. D. Leslie and R. M. Haines, *ibid.,* pp. 47–54.

(58) **"Airfield Pavement Evaluation,"** by H. J. Lichtefeld and R. M. Haines, *ibid.,* pp. 35–47.

(59) **"Evaluating the Load-Carrying Capacities of Military Airfields,"** by Gayle McFadden, *Civil Engineering,* April, 1945, pp. 167–169.

(60) **"Accelerated Traffic Tests for Flexible Airfield Pavements,"** by W. K. Boyd, *Proceedings,* Highway Research Board, National Research Council, Vol. 26, 1946, pp. 66–71.

(61) **"The Evaluation of Wheel Load Bearing Capacities of Flexible Types of Pavement,"** by L. A. Palmer, *Proceedings*, Highway Research Board, National Research Council, Vol. 26, 1946, pp. 72–99.

(62) **"Pavement Evaluation by Loading Tests at Naval and Marine Corps Air Stations,"** by L. A. Palmer and James B. Thompson, *ibid.*, Vol. 27, 1947, pp. 125–143.

(63) **"Pavement Performance Related to Soil Texture and Compaction,"** by K. B. Woods and L. E. Gregg, *ibid.*, Vol. 24, 1944, pp. 426–440.

(64) **"Mapcracking in Concrete Pavements As Influenced by Soil Textures,"** by Harold S. Sweet and K. B. Woods, *ibid.*, Vol. 26, 1946, pp. 286–298.

(65) **"Preliminary Studies of the Actual Service Lines of Pavements,"** by Robley Winfrey, *ibid.*, Vol. 15, 1935, pp. 47–60.

(66) **"Report of Committee on Permits for Oversize and Overweight Vehicles,"** by Rex M. Whitton, *ibid.*, Vol. 21, 1941, pp. 305–310. (*a*) p. 308.

(67) **"Wartime Changes in Volume and Composition of Traffic on Rural Roads in the United States,"** by John T. Lynch, *ibid.*, Vol. 22, 1942, pp. 375–384.

(68) **"Current Trends in the Volume and Characteristics of Highway Traffic,"** by John T. Lynch, *ibid.*, Vol. 23, 1943, pp. 350–362. (*a*) p. 351.

(69) **"Heavy Axle Load Frequency,"** by Thomas B. Dimmick, Vol. 25, 1945, pp. 354–363.

(70) **"Pavement Pumping Correlated with Traffic Loads,"** by K. B. Woods, F. H. Green, and Harold S. Sweet, *ibid.*, Vol. 27, 1947, p. 58.

(71) **"Report of Committee on Load Carrying Capacity of Roads As Affected by Frost Action,"** by C. L. Motl, *Highway Research Abstracts*, Highway Research Board, National Research Council, December, 1948, p. 49.

(72) **"Pumping of Rigid Pavements in Indiana,"** by K. B. Woods and T. E. Shelburne, *Proceedings*, Highway Research Board, National Research Council, Vol. 23, 1943, pp. 301–316.

(73) **"Subgrade Behavior,"** by J. W. Poulter, *Circular Series No. 41*, Illinois Eng. Experiment Station, Univ. of Illinois, Urbana, Ill., Vol. 38, No. 4, 1940.

(74) **"Report of Investigation of Pavement Pumping,"** *Abstracts and News Briefs*, Illinois Dept. of Public Works and Buildings, Div. of Highways, Vol. 7, Springfield, Ill., July, 1939.

(75) **"Final Report of Project Committee No. 1, Maintenance of Concrete Pavements As Related to the Pumping Action of Slabs,"** *Proceedings*, Highway Research Board, National Research Council, Vol. 28, 1948, pp. 281–310.

(76) **"Report of Committee on Maintenance of Joints in Concrete Pavements As Related to the Pumping Action of the Slabs,"** *ibid.*, Vol. 24, 1944, p. 226.

(77) **"Special Papers on the Pumping of Concrete Pavements,"** *Research Report No. 1D*, Highway Research Board, National Research Council, 1945.

(78) **"Maintenance Methods for Preventing and Correcting the Pumping Action of Concrete Pavement Slabs,"** *Current Road Problems No. 4-R*, Highway Research Board, National Research Council, September, 1947 (revised Ed.).

(79) **"Pavement Blowups Correlated with Source of Coarse Aggregate,"** by K. B. Woods, H. S. Sweet, and T. E. Shelburne, *Proceedings*, Highway Research Board, National Research Council, Vol. 25, 1945, pp. 147–168.
(80) **"Expansion Joint Practice in Highway Construction,"** by A. A. Anderson, *Transactions*, ASCE, Vol. 114, 1949, pp. 1159–1168. (*a*) pp. 1169–1172.
(81) **"History and Scope of Cooperative Studies of Joint Spacing in Concrete Pavements,"** by E. F. Kelley, *Proceedings*, Highway Research Board, National Research Council, Vol. 20, 1940, pp. 333–336. (*a*) p. 333.
(82) **"Transverse Joints in the Design of Heavy Duty Concrete Pavements,"** by H. W. Giffin, *ibid.*, Vol. 23, 1943, pp. 56–74.
(83) **"Experiments with Continuous Reinforcement in Concrete Pavements,"** by Earl G. Sutherland and Sanford W. Benham, *ibid.*, Vol. 19, 1939, pp. 193–196.
(84) **"Experiments with Continuous Reinforcement in Concrete Pavements,"** by H. D. Cashell and S. W. Benham, *ibid.*, Vol. 20, 1940, pp. 354–371.
(85) **"Experiments with Continuous Reinforcement in Concrete Pavement—A Five-Year History,"** by H. D. Cashell and S. W. Benham, *ibid.*, Vol. 23, 1943, pp. 35–45.
(86) **"An Experimental Continuously Reinforced Concrete Pavement in Illinois,"** by H. W. Russell and J. D. Lindsay, *ibid.*, Vol. 27, 1947, pp. 42–52.
(87) **"Preliminary Report on Current Experiment with Continuous Reinforcement in New Jersey,"** by William Van Breemen, *ibid.*, pp. 33–42.
(88) **"Continuously Reinforced Concrete Pavements Without Joints,"** by W. R. Woolley, *ibid.*, pp. 28–33.
(89) **"Effect of Experimental Subgrade Treatments on Pavement Faulting and Pumping,"** by E. A. Henderson and W. T. Spencer, *ibid.*, Vol. 26, 1946, pp. 319–340.
(90) **"Effects of Base Compaction on Maintenance Costs and Performance,"** by J. J. Forrer, *ibid.*, Vol. 19, 1939, p. 460.
(91) **"Subbases for Rigid Pavements,"** *Technical Bulletin No. 122*, Am. Road Builders' Assn., Washington, D. C., 1947.
(92) **"A Study of Course-Graded Base-Course Materials,"** by Edward A. Willis, *Public Roads*, Vol. 24, No. 9, 1946.
(93) **"Progress Report on California Experience with Cement Treated Bases,"** by T. E. Stanton, F. N. Hveem, and J. L. Beatty, *Proceedings*, Highway Research Board, National Research Council, Vol. 23, 1943, pp. 279–295.
(94) **"Base Stabilization with Tar,"** by Ralph D. Witt, *Proceedings*, Am. Road Builders' Assn., Washington, D. C., 1940, p. 677.
(95) **"Traffic Testing of Overlays on Rigid Airfield Pavements,"** by Herman L. Gaines, *Proceedings*, Highway Research Board, National Research Council, Vol. 25, 1945, pp. 85–95.
(96) **"Some Observations on Resurfacing Portland Cement Concrete Pavements with Bituminous Mixtures,"** by Wayne R. Woolley, *ibid.*, Vol. 26, 1946, pp. 311–319.